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Integral Frameworks of Climate Variability and Socio-Ecology Give Better Assessment of Mosquito-borne Diseases Dynamics in Africa

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ABSTRACT

Despite the significant impacts of climate variability on the transmission of mosquito-borne diseases globally, a lack of understanding of the fundamental relationship between them constitutes a major challenge. Although many parts of the world are at varying levels of increasing vulnerability to mosquito bites, Africa is particularly at the worst scenario of mosquito-borne disease transmission because of high severity of exposure to complex climate risks and low adaptive capacity. The study presents scientific progress on the extent of the impacts of climate on mosquito-borne disease studies in Africa, other factors influencing the disease transmission and the gaps in knowledge between 2020 and 2025. The paper was synthesized drawing on mosquito diseases transmission across sectoral chapters on human settlements, human population, ecosystem, water, livelihoods, health, and infrastructure. The result of studies shows that climatic factors (temperature, extreme events, and precipitation) play a dominant roles in the transmission of mosquito-borne diseases across the other earth system while biophysical factors (stagnant water bodies, poor urban sanitation systems, and deforestation), socioeconomic factors (low-income, poor urban infrastructure), and political factors (governance, legacy transformation challenges, and livelihood changes) exert complementary functions. Lack of high-resolution vulnerability integration in projection; empirical validation of adaptation assumptions; non-mortality health and social impacts exposure metrics; microscale urban exposure heterogeneity; validity of population projections in malaria hotspots; and long-term physiological acclimatization limits suggest the development of interdisciplinary studies integrating vulnerability indices to climate, population, and biophysical variables into a framework for the projection of mosquito-borne diseases distribution in the future.

Keywords: Mosquito-borne diseases, climate variability, fine-resolution, non-health impacts, population, vulnerability, .

1 INTRODUCTION

The history of mosquito-borne diseases is complex, such that the interplay of climatic, ecological, and vector biological factors defies a simplistic explanation, but the application of resources in a creative and organized fashion is required to discern the patterns of connectivity between them. The sixth assessment report of the IPCC clearly underscored the significance of understanding the challenges contributing to the transmission of mosquito-borne diseases in different parts of the ecological regions (Bera 2025). Understanding the multiple dimensions of vulnerability to disease transmission, along with responses to mosquito bites on humans, is among the determinants of mosquito-borne disease transmission in many parts of the globe. Despite the prevalence of mosquito-borne diseases in 100 countries recently, many people are unaware of the climate-induced disease outbreaks. Studies involving climate-induced diseases were restricted to a selected high-risk area, while several other parts of the country were often underrated as low-risk areas (Jeleff, Lehner et al. 2022). Thus, a lack of adequate understanding of the impacts of climate variability on mosquito-borne diseases contributed to a scarcity of data as well as early warning systems for the communities.

Unlike the Caribbean and South America regions, which have enjoyed several intervention programs, the African region has been mostly neglected in the dispensing of support, yet the most severely hit region of the world. For example, recent research progress in climate variability impacts on mosquito-borne diseases over the past three decades has shown that responses to climate variables in the Amazon and tropical rain forest, global climate change impacts, vulnerability of biodiversity, impacts of climate change in polar regions and sea ice loss, and sea level changes constitute the highest impacts. Tropical ecological resilience to climate change, tropical forest mitigation to climate change, habitat loss, shifts in species composition, and case studies of impacts on zoophilic species of mosquito had the second category of impact; tropical diseases mitigation to climate change and shift in species composition

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had a low impact but; tropical ecology of mosquito-borne diseases, climate technology, sea level rise, climate-change ecology and human health relationship in both tropic and polar regions, climate change and arctic ecological services and temperate and polar regions ecology was ranked lowest in terms of the impact factor (Gould, Álvarez-Berríos et al. 2024).

However, to bridge the research gaps in this area of study, a phenomenological model for climate-induced disease prediction was developed, and the model has been effective for calculating and capturing mosquito population dynamics between the mosquito and human system. Unfortunately, the model is highly dependent on local data for its operability. Because of this limitation and the need to make a realistic projection of epidemic dynamics across a broad spectrum of transmission settings, the mechanistic model was further developed (Okon, Falana et al. 2021). A mechanistic model has been used for the projection of climate-mosquito niche space in certain parts of urban areas. Despite the advantages of mechanistic models, validation of climatic data with vector and disease cases could be very difficult. In addition, the transmission model has not been able to assess the long-term impacts of climate change on disease transmission (Gorris, Bartlow et al. 2024). As an illustration, recent studies aimed at investigating the impacts of climate variability on mosquito transmission through the laboratory experiment showed that the survival rate of egg and adult phase is near-linear at 15ºC between 0% and 90% until the temperature reaches 20ºC before the survival rate start to decline to 60% at 30ºC; the time of egg to adult life development ranges between 60 days at 15ºC to 12 days at 20ºC until it continue to reduce to 6 days between 27ºC and 34ºC; the blood meal period of growth is 30 minutes of the time of landing on the host body which reaches its peak at 50% between 22ºC and 28ºC then start to decline up to 0% at 33ºC (Abbasi 2025).

The example above illustrates the importance of the phenomenological model for the prediction of behavior, and the geographical range of vector-diseases prediction, but the problem with these studies is the inability to capture temperature-dependent vector traits on important epidemic characteristics. However, vector-borne diseases provide ample opportunities to examine if climate-sensitive traits of mosquitoes that have been measured in the laboratory can accurately reproduce findings across a broad spectrum of dynamics observed in the field (Knoblauch, Heidecke et al. 2025). For example, studies have shown that the transmission of alboviral diseases occurred from a short span of weeks of endemic transmission to a longer span, ranging from seasons to several years of outbreaks. Because of the important roles played by the design of buildings, construction materials, and ventilation in the modification of indoor and outdoor environments, mosquito species now use a variety of ways to exploit the timing and location of human settlement microclimate to their maximum advantage (Ateutchia Ngouanet, Wanji et al. 2022).

For example, literature has revealed that *Anopheles gambiae* uses physiologic clocks to ensure that an adult species emerges from water either at sundown or in the early hours of the night, irrespective of the rate of metamorphosis. However, if the species is tested in the laboratory at constant illumination, the duration of the pupae stage is between 22 °C and 32 °C, and the pupae stage time may change to minimize emergence in daylight (Takken, Charlwood et al. 2024). What we can infer from the illustration is that other variables play a complementary role in climatic variables in the transmission of mosquito-borne diseases. The consideration of human activities, political and economic characteristics contributed to the complexities in climate-human infectious diseases transmission in many ecological regions, hence the development of several innovative strategies for the control of mosquito-borne diseases (Zhang, Zhang et al. 2017). This includes genetic approaches using Wolbachia-infected mosquitoes, genetically modified mosquitoes, and the sterile insect technique, among several other techniques. Although success has been recorded in the control of malaria, yellow fever, dengue, Zika virus, and Chikungunya, many scholars have identified challenges of its applicability, including the possibility of inducing parthenogenesis (reproduction without males), feminization of male species (turning genetic male species into female species), and cytoplasmic compatibility (unviable offspring) (Bhattacharyya and Roelke 2025). Remote sensing and GIS have been proposed to reduce uncertainties in epidemiological studies, as remote sensing analyzes spatial social, cultural, and socioeconomic data omitted by the models in the previous study. Remote sensing and GIS have an in-built system for analyzing the long-term spatial and temporal epidemiological data of climate-vector-diseases transmission (Chaminé, Pereira et al. 2021). Thus, remote sensing and GIS should be given a chance as we continue to deepen our understanding of climate-mosquito-borne diseases, and studies need to be replicated in the misconceived low-risk ecological regions.

2 METHODOLOGY

This systematic literature review was set out to address the state-of-the-art knowledge of the impacts of climate variability on the transmission of mosquito-borne diseases in Africa. The study specifically intends to answer the following research questions: to what extent is climate variability responsible for the transmission of mosquito-borne diseases in Africa? What are the other factors influencing the transmission of mosquito-borne diseases in Africa? And what are the gaps in knowledge? Thus, the review process involved extensive searching of high quality relevant journal that are indexed in scopus through the google scholar database, including Science Direct, Elsevier,

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Ecological Society of America report, Wiley, Sustainability, International Journal of Environmental Research and Public Health, Institute for Advanced Science, Social and Sustainable Future, PLOS neglected tropical diseases, Research gate, International Journal of Social Sciences and Humanities invention, MDPI, nature communication, scientific reports, BMC infectious diseases, and Taylor and Francis respectively. The study period 2020-2025 was selected due to the recent scientific updates within the last five years since the last review was conducted. The paper was synthesized drawing on mosquito diseases transmission across sectoral chapters on human settlements, human population, ecosystem, water, livelihoods, health, food systems, and infrastructure. The evidence of a shift in transmission of mosquito-borne diseases was assessed by considering the climatic factors influencing the transmission of the arbovirus infections through the lens of biological, ecological, and reproductive processes (Bera 2025). The process was used to draw challenges, including knowledge gaps for the African regions. The scientific studies of the impacts of climate on mosquito-borne diseases have been the major concern for scientists within the last few decades, as recent and future impacts of climate variability on the transmission of mosquito parasites in human settlements have been the leading topics of discussion (Gaza and Masere 2025).

2.1 Inclusion and Exclusion Criteria

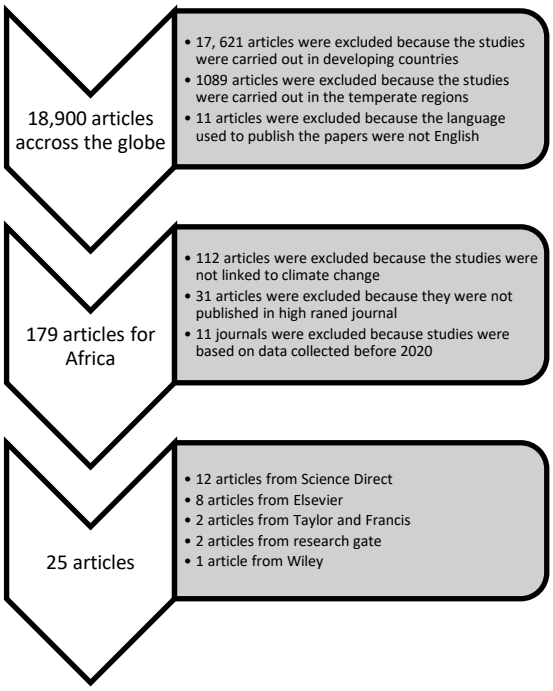
The inclusion criteria comprise studies that directly address the impacts of climate change on mosquito-borne diseases between 2020 and 2025 that were published in English, the prevalence of mosquito-borne diseases in Africa, factors influencing the transmission of mosquito-borne diseases in Africa, the analysis of the relationship between mosquito-borne diseases and climate variability, and the spatio-temporal distribution of mosquito-borne diseases in Africa. The exclusion criteria include similar studies that were carried out in other tropical regions and in temperate regions.

2.2 Search Items

Boolean operators were used in this study for the expansion and narrowing of searches of keywords using `AND` and `OR' across all the databases. The terms include Climate variability AND mosquito-borne diseases, Climate change AND mosquito-borne diseases, climate variability AND mosquito-borne diseases in developing countries, climate variability AND mosquito-borne diseases in Africa, and climate AND mosquito-borne diseases in developing countries. The search processes are crucial to adequately plan, follow protocol, and evaluate unbiased results. This is in accordance with (Adenuga, Iahad et al. 2015).

2.3 Literature Search Results

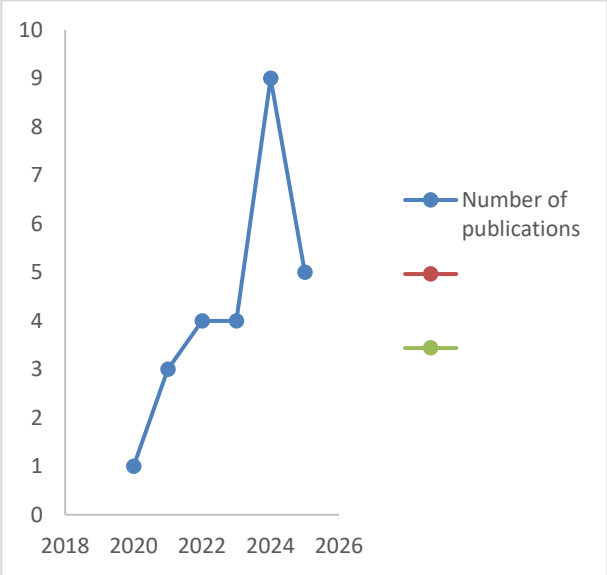
A total of 11,300 articles were identified through the google scholar search engine between 2020 and 2025, and each of those articles was subjected to gap analysis with a view to identifying and comparing authors name(s), title of articles, journal type, research gaps, methodology, contexts, theories, findings, limitations, recommendations, citation count, year of publication, quality assessment criteria respectively. The search results highlighted 25 papers that finally satisfied the set research questions with respect to the criteria for assessment. Figure 1 shows the diagram of the screening processes of the selected literature while Figure 2 shows the number of publications.



Source: Author, 2025

Figure 1: Screening processes of the selected literature

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Source: Author, 2025

Figure 2: Number of publications selected per year between 2020 and 2025

2.4 DATA ANALYSIS

Owing to lack of updated information on the state-of-the-art-impacts of climate change on mosquito-borne diseases in Africa since 2020, the empirical investigation of the impacts of climate variability in the transmission of mosquito-borne diseases in Africa, the non- factors influencing the transmission of mosquito-borne diseases, and the directionality of research in Africa becomes necessary as the result of the gap analysis was based on the recent (2020-2025) findings in the literature. The titles of articles, methodology, contexts, theories, findings, limitations, and research gaps are represented in terms of criteria as the Title is pre-coded CI, methodology, C2, context, C3, findings, C4, limitation, limitation, C5, research gaps, C6. At the end of the quality assessment of the various articles downloaded for the studies, a total of twenty-five (25) articles meet the pre-assigned criteria. Table I shows the Quality Assessment for the selection of articles for the study.

TABLE I: QUALITY ASSESSMENT FOR THE SELECTION OF ARTICLES FOR THE STUDY

Papers	C1	C2	C3	C4	C5
1	1	1	1	1	1
2	2	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1
6	1	1	1	1	1
7	2	1	1	1	1
8	1	1	0	2	1
9	1	1	1	1	1
10	1	1	1	1	1
11	2	1	1	1	1
12	1	1	1	1	1
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	2	1	1
16	1	1	1	1	1
17	2	1	1	1	1
18	1	1	1	1	1
19	1	1	1	1	1
20	2	1	1	1	1
21	1	1	1	1	1
22	1	1	1	1	1
23	1	1	1	1	1
24	1	1	1	1	1
25	1	1	1	1	1

Note that each criterion is ranked at 2 marks, any paper that has the overall marks between 5 and 10 satisfies our criteria. The authors presented only the 25 articles that satisfy the criteria for this study to maximize space. The comprehensive list may be sent on request.

Despite the increase in the magnitude and trends in the transmission of mosquito-borne diseases in Africa, there is a limited understanding of the relationship between the climate and non-climatic factors and the mosquito-borne diseases within the One Health framework. The key to addressing the increasing threats of mosquito-borne diseases is to integrate several contributory factors that are pertinent to the transmission of diseases. Most of the studies focused on the impacts of climate variability on the transmission of mosquito-borne diseases within the African context, and the primary data utilized numerical modelling, descriptive and inferential statistics, remote sensing, and geographic information systems. Systematic reviews constitute the other sources of data for meta-analysis. The study was based on the theories of ecological behavior and adaptive ecology of vectors, climate variability principles, susceptible-infected-resistance mathematical frameworks, geographic information science and robust surveillance principles, one-health concept, infectious diseases risk frameworks, and climate-driven behavioral and physiological plasticity in vectors.

3 RESULTS AND DISCUSSION

The result of the analysis identified climatic factors (temperature, extreme events, and precipitation), biophysical factors (stagnant water bodies, poor urban sanitation systems, and deforestation), socioeconomic factors (low-income, poor urban infrastructure), and political factors (governance, legacy transformation challenges, and livelihood changes), respectively. The main study limitations include heterogeneity of methodologies, lack of adequate behavioral data of vectors, changes in biophysical dynamics, financial constraints, and uncertainties in the current laboratory-based models. The main research gaps include a lack of fine-resolution climate data, a lack of fine-resolution studies

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integrating demographic data, genotype data, vulnerability data, and climate data in the studies, lack of long-term projection models on future range dynamics of mosquito-borne diseases distribution, biophysical characteristics, and socioeconomic characteristics.

3.1 Impacts of Climate Variability on the Transmission of Mosquito-borne Diseases

Results have predicted a latitudinal shift in the expansion of the territorial bases of mosquito-borne diseases in Africa due to variability in temperature, rainfall, and extreme events. For example, the frequent occurrence of floods has been accompanied by high cases of malaria due to malaria attacks in many households in sub-Saharan Africa (SSA). Such climatic elements are responsible for a weak surveillance system, enhanced adaptation of disease vectors through behavioral shifts, physiological changes, and increased transmission efficiency and geographical ranges. Thus, high temperature and rainfall promote larva development and elongate the breeding season. The recent change in the geographical distribution and dimension of occurrence of malaria, yellow fever, and dengue infection globally has assumed a deadlier proportion, and this constitutes concern among scholars in several parts of the world. Climate variability represents a potential factor influencing the high frequency of occurrence of mosquito-borne diseases globally.

An increase in the global temperature is attributed to the expansion in the spatial distribution of *Aedes aegypti* mosquito, which is the primary vector of dengue, Chikungunya, and *Zika* virus. Increase in rainfall patterns threatens the transmission of mosquito-borne diseases, and humidity is strongly associated with the high surface area to volume of a mosquito species (Gaza and Masere 2025). For example, about 76% of all known mosquito species belong to *Anopheles*, *Aedes*, and *Culex* species, which are responsible for 1 billion diagnostic cases of mosquito-borne diseases and more than 1 million deaths globally every year. Despite that climate directly influences the intensity of transmission of diseases among the pathogen, human, and non-human hosts, the degree of such influences is determined by multiple factors, including the pathogen exposure, history of the disease vector, and human mobility, but the mechanisms underlying the ecological effects of climate seem to exert the strongest influence (Charnley and Kelman 2024).

Because climate change and mosquito-borne diseases are strongly linked, vulnerability to infection by the mosquito-borne vectors is also determined by the capacity to adapt to climate change. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) decried poor understanding of climate-mosquito-borne diseases interactions among the challenges confronting the science of climate change impacts and adaptation globally (Gizaw, Salubi et al. 2024). However, recent studies show that although the relationship between climate and mosquito-borne diseases is as old as man on Earth, the scientific investigation of climate-mosquito transmission of diseases began around the mid-20th century. Although the abundance and contact between mosquitoes and people depend on the availability of mosquito larval and pupal breeding habitats, the optimum temperature suitable for mosquito timing and outbreak, feeding, and nesting throughout the year is 25 °C (Gizaw, Salubi et al. 2024). On the other hand, *Aedes gambiae* specie thrives better indoors in Sudan at a mean temperature of 42 °C despite the outdoor temperature of 55 °C by appearing from the thatch of buildings after sunset, feeding through the midnight, and ovipositing early in the morning (Egid, Coulibaly et al. 2022).

However, studies within the last three decades have shown that the impacts of climate variability on the transmission of mosquito-borne diseases have increasingly shifted from significant to a threatening proportion, which prompted major worries globally. Recent studies have investigated the impacts of climate variability on vector-borne diseases (Franzen and Bahr 2024). The recent disappearance of *Aedes aegypti* by a non-native species of mosquito known as *Aedes Albopictus* in Memphis, the southern United States of America, is major evidence of the global warming on human-mosquito-borne diseases in many parts of the world (Abbasi 2025).

3.2 Other Factors Affecting Transmission of Mosquito-borne Diseases

3.2.1 BIOPHYSICAL FACTORS

Land use data, stagnant water, highly degraded areas, and poor urban infrastructures have been strongly linked to the emergence and re-emergence of mosquito-borne diseases in Africa. However, the links between climate, biophysical factors, and mosquito-borne diseases are poorly understood (Gambo, Binti Roslan et al. 2024). The limited scope of research due to financial constraints has been attributed to a poor understanding of the relationship between climate and the biophysical factors. Despite the activation of early warning systems in Nigeria, Kenya, and several other countries in the SSA, deforestation, unplanned and uncontrolled urbanization, and poor sanitation have worsened the increasing trends in transmission of mosquito-borne diseases in Africa and necessitate urgent attention. Land clearing, bush burning, and fossil fuels, which release greenhouse gases into the atmosphere, began to increase as the frequent occurrence of extreme precipitation in the northern hemisphere provides an excellent example of the anthropogenic cause of climate change that accompanied global warming. Evidence of human-induced climate change is the multiplication of mosquito and parasite traits that are

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favorable to disease transmission and pathogens' metabolic processes, which include reproduction, development, survival, biting rate, and intrinsic incubation period.

Thus, compared to the natural cause of climate change, anthropogenic activities have led to rapid changes in the ecological regions around the world. For example, urbanization, overpopulation, and industrial emissions have not only changed the atmospheric composition but also altered the ecological resources (Sen Gupta and Tiwari 2021). The climate impacts on mosquito-borne diseases have been studied in the fields of public health, epidemiology, zoology, anthropology, and medical sciences. Most of these studies have shown that despite the state-of-the-art evidence of climate change impacts on human health, a lack of understanding of the links between the climate and mosquito-borne diseases constitutes a challenge among scholars in most parts of the world (Giesen, Roche et al. 2020). Caribbean and South America are reported to be highly vulnerable to climate extremes such as precipitation extremes and high ultraviolet radiation, but many residents are unaware of the causal links to the prevailing vector-borne diseases in the area.

The above example underscores the importance of roles played by non-linear relationships of standing water from extreme precipitation events and water storage practices during drought conditions on the transmission of mosquito-borne diseases. Scientific evidence has shown that sea ice depletion will have great impacts on the Arctic animals as well as native residents of the area. For example, an increase in the temperature of the sea ice regions may probably lead to increased attacks on animals and the human population due to the continuous increase in the number of stable endemic Aedes species (Ivanov 2023).

3.2.2 SOCIOECONOMIC FACTORS

This section explores the vulnerability to climate-induced mosquito-borne diseases in Africa by considering the impacts of climate variability as well as critical drivers of climate-induced mosquito-borne disease outbreaks in Africa. The resilience of different ecological regions to climate variability has constituted a global concern, as climate variability not only affects the vegetation resources but also changes the physical composition of the environment, with cascading effects on human hospitalization. Poor water management systems, rising uncontrolled urbanization, overpopulation, and poor urban waste disposal systems are among the environmental factors contributing to the high temperature and rainfall variability in Africa. Vulnerability to vector-borne diseases is unevenly distributed spatially because of differences in susceptibility to the effects of climate-induced bites by the mosquito vectors. These dimensions of susceptibility to mosquito-borne diseases affect each other and contribute to the directional and dynamical effects of climate, making the understanding of the relationship between climate and mosquito-borne diseases a novel scientific debate globally.

For example, water storage practices during the drought may boost water availability, mosquito abundance, and mosquito-borne diseases. For example, about 620,000 deaths were reported from malaria in 2017, with annual death rates of over 400,000. Similarly, yellow fever is the second most fatal mosquito-borne disease after malaria, and yellow fever has been recently categorized as a re-emerging disease in Africa. Yellow fever is characterized by high fever, jaundice, and spontaneous bleeding (Seka, Zhang et al. 2022). Although only a few pieces of evidence have been compiled about the impacts of climate change on mosquito-borne diseases in the biodiversity-rich tropical rain forest ecosystems, however, several parts of Africa where water drought is imminent have been projected to harbor mosquito vectors, which may lead to disease epidemics (Lombe, Carvalho et al. 2024). The recent occurrence of prolonged drought in many parts of Africa informed the need to scale up early warning systems and drastic adaptation measures. Socioeconomic processes, resource access, changes in livelihood, including the intersectional vulnerability, also contribute to climate-induced mosquito-borne diseases (Odongo, Schrieks et al. 2025).

The macro socioeconomic processes influencing the vulnerability to diseases include colonial legacies and post-colonial development pathways, governance, and adaptation and mitigation actions. These processes interact to orient the mesoscale system of resource access, livelihood, and social differentiation at the community level (Biswas and Nautiyal 2023). For example, financial misappropriation and huge external debts interact to discourage private and multilateral intervention and reduce the State's capacity to strengthen public investment in mosquito eradication programs. The severity of the impacts of climate variability on mosquito-borne diseases in Africa depends on the extent of environmental degradation illicit cash flow varies from country to country, or from one ecological region to another ecological region. Thus, in terms of unsustainable oil and gas exploration to siphon public funds, Nigeria, Sudan, and Cameroon may be highly vulnerable; Botswana, South Africa, and the democratic republic of Congo ranked among the African countries where illicit flow of cash through mining of mineral resources is common (Permatasari and Ismail 2024).

The overall effect of illicit capital flow is that a country or region may not be able to fund infrastructural projects as well as program and sustainable government policy that will control mosquito-borne diseases. Studies have noted that the common features of African government expenditures on urban areas development far exceed the expenditures on the development of rural communities (Leykun Fisseha 2022). Some studies have found that rural communities were the worst hit by the impacts of climate variability on the

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transmission of mosquito-borne diseases because of a lack of climate change mitigation and adaptation plans by the government. Therefore, neglecting local communities at the expense of urban areas in the area of adaptation may further compound the multiplication of mosquito-borne diseases among the African population (Roy, Kumar et al. 2024). Despite the departure of colonial masters many decades ago, many African countries have not stopped power imbalances and unequal trade relations that were typical of the colonial masters' system of government. The marginalization of the South from northern Nigeria, as well as the neglect of northern Ghana in favor of Southern Ghana, has its roots in the colonial system of exploiting mineral resources, agricultural products, and cheap labor for the economic advantages of the government (Wu 2024).

The consequences of colonial legacy include the destruction of biodiversity and exposure of the land and water resources to anthropophilic mosquito habitats. The colonial legacy of power imbalances also contributed to the wide divide created between the few resource-rich farmers and millions of rural farmers during the structural adjustment program about four decades ago. Such cases of partiality in resource distribution in Ghana and Nigeria were used as a perfect example of how drivers of vulnerability on the transmission of mosquito-borne diseases vary between and within different ecological regions in Africa (Hope 2025). Because of diversity in the vulnerability context in Africa, scholars have canvassed for multi-scalar assessment incorporating both responses and intersectional dynamics for the explanation of the probability of malaria and yellow fever outbreaks and the ability to mitigate their effects (Hope 2025). The intervention of gender, age, and travel status into the wider dimension of social vulnerability seeks to balance the unequal power relations and differential access to resources with a view to controlling the extrinsic incubation period of mosquitoes, which is the chances of human-mosquito-borne diseases transmission and the pace at which diseases develop inside the mosquito. in the various ecological settings of Africa (Ayanlade, Smucker et al. 2023).

Intersectional vulnerability definition ranges from concern for intra-group heterogeneity, concern for agency of vulnerability, as well as a place-based understanding of the means by which social gradients are constructed in a singular vulnerability group (Kuran, Morsut et al. 2020). Intersectional vulnerability seeks to capture the multiple drivers of vulnerability into consideration by factoring in people of different socioeconomic groups in the mitigation and adaptation processes to mosquito-borne diseases. For example, women are always the potential target for any possibility of outbreaks of mosquito-borne diseases in every household because women are traditionally restricted in movement whenever there is a disease outbreak, and women are also the least likely to mitigate the transmission of the diseases (Kuran, Morsut et al. 2020). What is apparent from the literature on vulnerability assessment of mosquito-borne diseases is that uncontrollable urbanization growth rate, overpopulation, and power inequality are occurring at macro-scale levels and are highly influencing the transmission of mosquito-borne diseases in Africa. Secondly, non-climatic factors played significant roles in the transmission of diseases, and the process of transmission is a non-linear, complex cause-effects relationship and may probably be responsible for epidemic cases (Al-Eitan, Alnemri et al. 2024).

Finally, the achievement of effective climate adaptation to mosquito-borne disease outbreaks is premised on integrating multiple factors of vulnerability and broader development trends in Africa, mosquito-borne disease vectors and transmission systems, including the effects of mitigation and adaptation, using relevant statistical analysis and sophisticated models (Giesen, Roche et al. 2020). There is therefore a need for systematic research to deepen our understanding of the relationship between climate variability and mosquito-borne diseases in Africa. Extreme poverty is a limiting factor contributing to the multiplication of mosquito-borne diseases in Africa, as low-income groups are highly vulnerable to mosquito bites because of their relative exposure to stagnant water, slum shelters, and unplanned communities, compared to the wealthy, educated classes who enjoy adequate infrastructure necessary to repel and manage disease vectors' breeding habitats (Avramov, Thaivalappil et al. 2023). Low capacity to cope with mosquito transmission is a major feature of the low-income categories of the human population in several communities in Africa.

The capacity to cope with the increasing threats of mosquito-borne diseases includes human activities, political and economic resources to manage people, livelihoods, ecological settings, and infrastructures. Recent studies have reported that the number of species of mosquitoes has increased from 3500 to 3528 as a result of climate change, and one of the highest recorded increases in malaria was obtained in many parts of Central America, the northern half of South America, most parts of tropical and sub-tropical Asia, the Mediterranean, and several parts of the former Soviet Union (Al-Eitan, Alnemri et al. 2024). The literature has apparently shown that there are many uncertainties regarding the impacts of climate variability on human systems, including their severe social, cultural, and economic effects. Uncertainties are also abounding with respect to the transmission of mosquito-borne diseases between the multiple human climate players, as well as different constructions, assumptions, and time frame models on the possible impacts of climate variability at different ecological regions. Irrespective of these uncertainties, the scientific consensus opinion is that the impacts of climate variability on the occurrence of mosquito-borne diseases in human social, cultural, and economic lives are likely to be worse in the future (Baum 2024).

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3.2.3 Political Factors

Recent studies have shown that even though many African countries are currently enjoying sovereignty because of their independence from colonial masters, a significant number of these countries remain neo-colonized, as the remnants of colonialism are still reflected in their governance systems. For example, inequities are major features of economic discourse in the governance system because of impartiality in the distribution of resources across the population gradients. Marginalization, lack of fairness, and equity by the government in power serve as an excellent justification for the people in the Niger Delta region of Nigeria to begin to advocate for the creation of the Biafran Republic. A similar reason can be found in Southern Ghana versus Northern Ghana. A major consequence of large barriers between the poor and the rich population characteristics is the unavoidable increase in the transmission of mosquito-borne diseases. Similarly, despite that in the year 2020, mosquito-borne diseases accounted for about 241 million illnesses and 627,000 deaths, yet about 1million deaths are estimated annually due to climate-induced mosquito-borne diseases worldwide.

Interestingly, since 1955, the World Health Assembly has been rolling out several intervention programs with the hope of eradicating the mosquito-borne diseases globally, including the malaria eradication program, the *Aedes Aegypti* eradication campaign, the use of Artemisinin-based combination therapies (ACTs), and insecticide-treated nets (ITNs) (Thellier, Gemegah et al. 2024). Although notable successes were recorded within the first year of its implementation, the programs were later discontinued in many parts of the world due to the protracted increase in frequency of extreme climate events globally. However, diseases reappeared after a few years of intervention in many parts of the world (Mue and Ogbe, 2025). The evidence above has clearly shown that the major and critical challenges confronting many ecological regions are climate variability, which is causing continuous expansion in the spatial distribution of mosquito-borne diseases in many parts of the world. Because of climate change, which has extended to the Arctic's ecological regions, mosquito-borne diseases have also expanded their coverage towards the Arctic regions, and the rate of warming of the Arctic regions has been reported to be more than twice the global average (Okon, Falana et al. 2021).

For example, sea ice losses due to temperature increase have led to what scientists referred to as Arctic amplification, and mosquito pathogens take advantage of the opportunity to sequester, and a mosquito vector of the st. louis' encephalitis virus, named *Culex pipens*, together with the recently imported West Nile virus, have been discovered in North America as far north as New Brunswick and new Scotia, Canada (Wunderling, Willeit et al. 2020). Several climate models have predicted that the Arctic regions are more likely to be ice-free between 2050 and 2100. What this suggests is that there is a high probability of a latitudinal shift in mosquito species such as *Aedes albopictus* towards the polar regions by the end of this century.

3.3 Research Gaps on Climate-Mosquito-Borne Diseases Studies

Assessing the impacts of climate variability on mosquito-borne diseases helps prevent threats to ecological systems, the built environment, and socioeconomic livelihoods. Recent insights from the literature have identified some research gaps that require urgent attention. The research gaps include high-resolution vulnerability integration in projection; empirical validation of adaptation assumptions; non-mortality health and social impacts exposure metrics; microscale urban exposure heterogeneity; validity of population projections in malaria hotspots; and long-term physiological acclimatization limits (Fox, Agyemang et al. 2024). Given the growing momentum of well-modelled exposure, projections rarely integrate dynamic, high-resolution, local-scale socioeconomic variable indices with climate and population data to project accurate actual risks of malaria attacks (Sun, Zhang et al. 2024). Because of this deficiency, there is a need to develop an integrated modelling framework that dynamically integrates high-resolution climate projections, population scenarios, and granular, transient vulnerability indices to quantify future mosquito-borne disease distribution (Meena and Vishnuvardhan Reddy 2021).

Secondly, although projections of malaria often include simplified assumptions about physiological and behavioral adaptation, we argue that a more explicit concern for empirical validation of those assumptions is needed, especially under extreme, unprecedented future climate conditions in Africa. Indeed, the growing evidence of simplified assumptions about physiological and behavioral adaptation to mosquito-borne diseases points to an urgent need for long-term cohort studies and natural experiments determining the effectiveness and limits of adaptation strategies under varying extreme events and socioeconomic conditions (Li, Liu et al. 2025). Studies from the existing literature also revealed that emphasis has recently been placed on mortality exposure, whereas there is a need for a deeper understanding of future exposure to morbidity, impacts on cognitive function and learning, reduction of labor productivity, and social disruption, which are currently underexplored in the literature. Thus, robust exposure metrics and mosquito-borne disease projection models for a wider range of health outcomes, including reduced labor productivity and social impacts, need to be developed.

Despite that, UHI projections are well recognized, but a lack of spatial resolution to capture extreme microscale variation

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in temperature exposure within the urban settings, driven by complex urban morphology, vegetation, and infrastructure, constitutes a major limitation. Therefore, application of very high resolution (<100 m) urban climate models, coupled with detailed population distribution data for the fine-scale intra-urban heat exposure disparities, should be given urgent research priority (Diem, Nguyen et al. 2024). Current mosquito risk exposure projection strongly relies on SSP population grids, whereas there are uncertainties in the validity of such predictions over the regions being affected by extreme future events. Despite the significant climate-driven migration away from the affected regions that often occurs, such a factor is not often dynamically considered in most models (Gorris, Bartlow et al. 2024). Thus, research integrating dynamic models of climate migration feedback into population projection for high-temperature projection regions should be given immediate attention. Although short-term acclimatization to heatwaves is well-documented in the literature, the long-term human physiological adaptation to suppressive extreme events over decades, especially among vulnerable populations in Africa, is poorly understood. Investigating the long-term adaptive capacity and potential thresholds for different populations under chronic climate scenarios should therefore be a leading research priority.

4 CONCLUSION

African countries, because of the multiplying effects of global climate variability, are the most vulnerable to mosquito-borne diseases due to their low capacity to mitigate and adapt to the situation. But assessing vulnerability to mosquito-borne diseases in Africa is going to be a daunting task without incorporating the drivers and responses to the transmission of mosquito-borne diseases across the ecological regions (Fonjong, Matose et al. 2024). This includes the consideration of interacting drivers as well as intersectional dynamics in the subsequent vulnerability assessment methodologies. However, the incorporation of interacting drivers and intersectional dynamics may involve the use of broader qualitative and indigenous knowledge methodologies, which have not been given prominence in the literature (Ayanlade, Smucker et al. 2023). One of the benefits of such analysis is the possibility of spotting the benefits of reducing transmission of mosquito-borne diseases across the broad social gradients, and the socio-ecological approach will, for the first time, incorporate a place-based transmission of mosquito-borne diseases. This may require the collaboration of relevant stakeholders to study the potential impacts of individuals as well as group responses to a given incidence of mosquito-borne diseases in a community or certain ecological region.

(Osobajo, Oke et al. 2023). Recent studies have shown that the magnitude and direction of cause-and-effect relations between the vectors and diseases are unclear, which may have contributed to qualitative and quantitative research gaps, as longitudinal methods will foster a deeper understanding of temporally compounding vulnerability to disease transmission and time series records of its climatic patterns. Studies have shown that despite the overall review of scientific research on the impacts of climate variability on ecological systems, population, human settlements, epidemiology, and public health, this review revealed that there is variability in the magnitude and direction of responses to climate variability globally. The scientific obligation of examining climate-mosquito-diseases distribution must take responsibility for the traditional options of field data collection, which have been restricting the research capability of examining responses to climate variability. Otherwise, the use of a socio-ecological approach, which entails qualitative, indigenous knowledge and place-based vulnerability assessment, should be given a chance.

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